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(54) Abstract Title

Apparatus and method measures change in position of stage mirror with air turbulence compensation

(57) An apparatus and method that measures the change in the position of a stage mirror (22) with respect to a reference mirror (21) when the stage mirror moves between two positions. Air density is measured at the same time as the mirror distance is measured to provide air turbulence compensation. The apparatus (10) includes a light source (11) for generating first and second coincident light beams, the first light beam (12) having a wavelength λ_1 and the second light beam (13) having a wavelength λ_2 where $\lambda_1 = M \lambda_2$. The first light beam (12) includes two orthogonally polarised components differing in frequency by a first beat frequency, $F_{ref}(\lambda_1)$, and the second light beam (13) includes two orthogonally polarised components differing in frequency by a second beat frequency, $F_{ref}(\lambda_2)$, where $F_{ref}(\lambda_2) = M F_{ref}(\lambda_1)$, and M is an integer greater than 1. A polarisation dependant beam splitter (17) directs one of the orthogonally polarised components of each of the light beams to the reference mirror (21) and the other of the orthogonally polarised components of each of the light beams to the stage mirror (22). The polarisation dependant beam splitter (17) also recombines the orthogonally polarised components after they have been reflected by either the reference mirror (21) or the stage mirror (22). The light intensities of the recombined light beams are measured in first and second detectors (23 and 24). The outputs of these detectors are combined to provide an optical path measurement and a correction term that corrects for the density of air along the measurement path, and hence, corrects for any air turbulence.

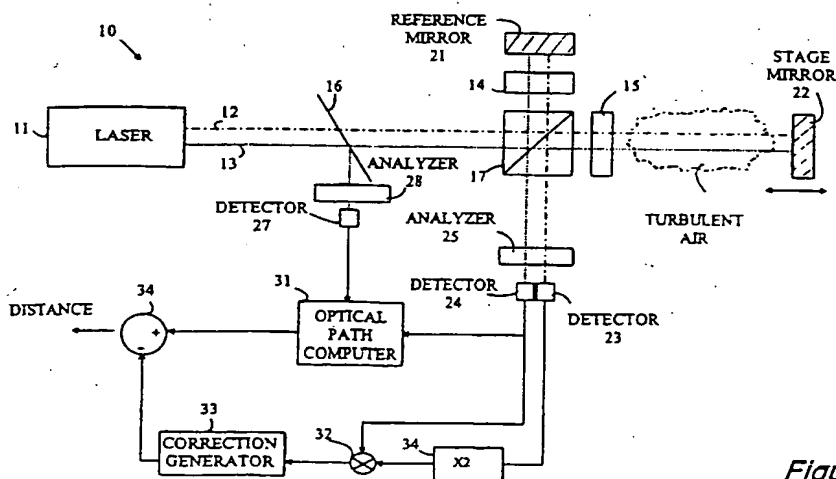


Figure 1

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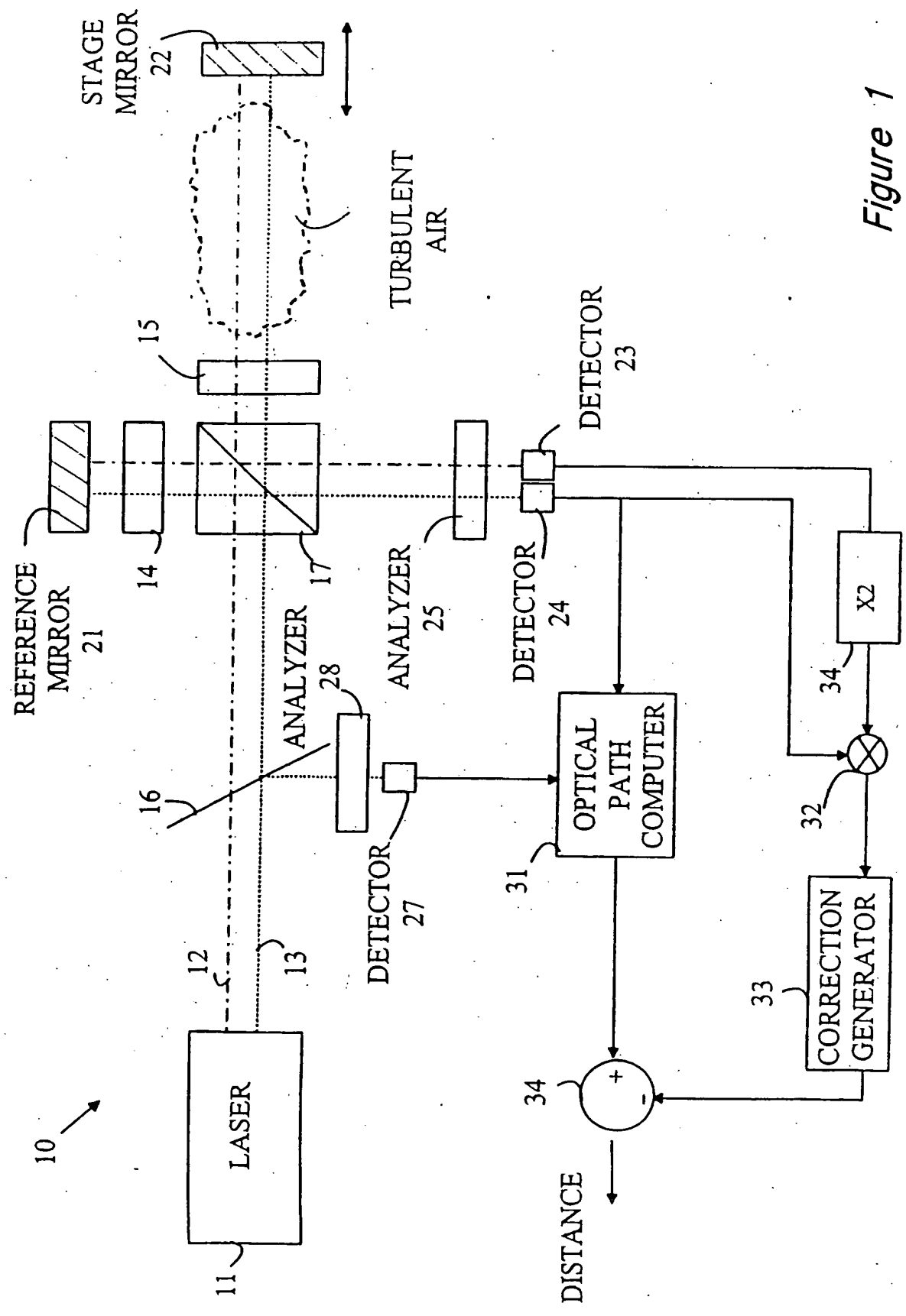


Figure 1

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APPARATUS FOR MEASURING CHANGE IN POSITION OF STAGE MIRROR

This invention relates to apparatus for measuring the change in position of a stage mirror, for example for a distance measuring interferometer that compensates for the effects of atmospheric turbulence on interferometric measurements.

Interferometers based on laser beams are used to make highly accurate displacement measurements, such as required in the control of wafer steppers used in integrated circuit (IC) manufacturing. In a distance-measuring laser interferometer, light from a laser source is split into two beams. The reference beam is reflected from a stationary reference mirror, while the measurement beam is reflected from a moving measurement mirror. The beams are recombined at a detector. The optical intensity of the combined beams depends on the difference in optical length between the reference and measurement paths. Measurements of the optical path to an accuracy of a fraction of the wavelength of the laser are routinely obtained.

Distance-measuring interferometers are typically divided into DC and AC interferometers. In a DC interferometer, the laser emits a single frequency. Only when the measurement mirror is moving is the interference signal time-varying. When the measurement mirror is stationary, the interference signal is a constant. Unfortunately, disturbances such as laser power drift and electronic noise can be easily misinterpreted as a motion signal, especially when the measurement mirror is stationary.

In an AC interferometer, the laser emits two optical frequencies with orthogonal polarizations. The two optical frequencies differ by a small amount. One of the beams is directed along the reference path while the other is directed along the path to be measured. The frequencies are separated with a polarization-dependent beam splitter, with one frequency going to the reference mirror and the other going to the measurement mirror. When the beams are recombined, a beat frequency at the difference in optical frequencies is created.

When the measurement mirror moves, the beat frequency shifts because of the Doppler shift induced by the motion. In this arrangement, the distance measurement is obtained by taking the difference of the frequency observed when the measurement mirror is moving and the frequency when both mirrors are stationary. This later frequency is obtained by directing a portion of the laser's output at an appropriate detector to generate the beat frequency. Since only the component of the noise within the frequency band between the reference beat frequency and the beat frequency observed when the mirror is moving can interfere with the signal, the effects of noise are substantially reduced in AC interferometers.

Thus, the detector generates an AC signal when the measurement mirror is stationary as well as when it is moving. It is easier to reject noise with a time-varying signal than with a constant one. Therefore, AC interferometry is more accurate than DC due to its superior ability to reject noise

The distance measured by observing the above-described difference in frequencies, or by counting fringes in the case of a DC interferometer, is the difference in the optical path between the reference arm of the interferometer and the arm containing the moving mirror. In most cases, the parameter of interest is the difference in physical distance. The physical path length is the optical path length divided by the average index of refraction of the air on the path traversed by the light beams. Hence, the interferometric measurement must be corrected for the index of refraction of the air along the path. In practice, the air along the measurement path may be turbulent, particularly in the region surrounding the wafer stage of a stepper. The index of refraction depends on the local air density along the path. Hence, unless the index of refraction is known on the actual path at the time the measurement is being made, errors will be made in the conversion from optical path length to physical distance. As the feature sizes in circuits shrink, the errors resulting from air turbulence can lead to serious position-measurement errors. Hence, methods for measuring the index of refraction simultaneously with the optical path length have been proposed.

One method for simultaneously determining the density of air and the physical path length is to use the measured relationships between the index of refraction of air, the density of air, and the optical path length. Since the index of refraction changes with wavelength, the average density, and hence, index of refraction can be deduced by measuring the optical path length at two or more wavelengths.

Measurement systems based on measuring the optical path length at two widely separated frequencies are known to the art. For example, Lis (U.S. Patent 5,404,222) describes a system in which two lasers are utilized to measure the optical path length at different frequencies. The system taught by Lis requires a much more complex optical system than that utilized in a conventional AC interferometer. This system requires 3 wavelengths, and multiple distance measurements to correct for air turbulence. In addition, the system has a poor signal-to-noise ratio because it relies on non-resonant second harmonic generation to provide the multiple wavelengths. The system also relies on expensive optical techniques to generate a correction signal.

The present invention seeks to provide an improved AC interferometer.

According to an aspect of the present invention, there is provided apparatus for measuring the change in position of a stage mirror with reference to a reference mirror when said stage mirror moves between first and second positions, said apparatus comprising: a light source for generating first and second coincident light beams, said first light beam having a wavelength λ_1 and said second light beam having a wavelength λ_2 where $\lambda_1 = M\lambda_2$, said first light beam comprising two orthogonally polarized components differing in frequency by a first beat frequency, $F_{ref}(\lambda_1)$ and said second light beam comprising two orthogonally polarized components differing in frequency by a second beat frequency, $F_{ref}(\lambda_2)$, where $F_{ref}(\lambda_2) = M F_{ref}(\lambda_1)$, M being an integer greater than 1; a polarization dependent beam splitter for directing one of said orthogonally polarized components of each of said light beams to said reference mirror and the other of said orthogonally polarized components of each of said light beams to said stage mirror and for recombining said orthogonally polarized components after said orthogonally polarized components have been reflected by either said reference mirror or said stage mirror; a first detector for detecting the intensity of light in said first light beam after said orthogonally polarized components of said first light beam have been recombined by said polarization dependent beam splitter, said first detector generating a first detector signal having a magnitude equal to the light intensity at said first detector, said first detector signal oscillating at an instantaneous frequency of $F_1(t)$; a second detector for detecting the intensity of light in said second light beam after said orthogonally polarized components of

said second light beam have been recombined by said polarization dependent beam splitter, said second detector generating a second detector signal having a magnitude equal to the light intensity at said second detector, said second detector signal oscillating at an instantaneous frequency of $F_2(t)$; a reference signal generator for generating a reference signal that oscillates at said second beat frequency; an optical path measurement circuit for measuring the difference in the number of oscillations of said second detector signal and said reference signal generator during the period in which said stage mirror moves from said first position to said second position and for generating an optical path signal indicative of said difference; and a correction term circuit for measuring the number of oscillations in a signal comprising $MF_1(t) - F_2(t)$ during the period in which said stage mirror moves from said first position to said second position and generating a correction signal indicative of said measured number of oscillations.

According to another aspect of the present invention, there is provided a method of measuring the change in position of a stage mirror with reference to a reference mirror when said stage mirror moves between first and second positions, said method comprising: generating first and second coincident light beams, said first light beam having a wavelength λ_1 and said second light beam having a wavelength λ_2 where $\lambda_1 = M\lambda_2$, said first light beam comprising two orthogonally polarized components differing in frequency by a first beat frequency, $F_{ref}(\lambda_1)$ and said second light beam comprising two orthogonally polarized components differing in frequency by a second beat frequency, $F_{ref}(\lambda_2)$, where $F_{ref}(\lambda_2) = M F_{ref}(\lambda_1)$, M being an integer greater than 1; directing one of said orthogonally polarized components of each of said light beams to said reference mirror and the other of said orthogonally polarized components of each of said light beams to said stage mirror and for recombining said orthogonally polarized components after said orthogonally polarized components have been reflected by either said reference mirror or said stage mirror; detecting the intensity of light in said first light beam after said orthogonally polarized components of said first light beam have been recombined, generating a first detector signal having a magnitude equal to the light intensity at said first detector, said first detector signal oscillating at an instantaneous frequency of $F_1(t)$; detecting the intensity of light in said

second light beam after said orthogonally polarized components of said second light beam have been recombined, generating a second detector signal having a magnitude equal to light intensity; said second detector signal oscillating at an instantaneous frequency of $F_2(t)$; generating a reference signal that oscillates at said second beat frequency; measuring the difference in the number of oscillations of said second detector signal and said reference signal during the period in which said stage mirror moves from said first position to said second position and for generating an optical path signal indicative of said difference; and measuring the number of oscillations in a signal comprising $MF_1(t) - F_2(t)$ during the period in which said stage mirror moves from said first position to said second position and generating a correction signal indicative of said measured number of oscillations.

The present invention can provide an interferometer that automatically compensates for turbulence along the measured optical path; and/or an interferometer that is less complex than prior art interferometers that compensate for turbulence.

The preferred embodiment provides apparatus for measuring the change in position of a stage mirror with reference to a reference mirror when the stage mirror moves between first and second positions. The apparatus includes a light source for generating first and second coincident light beams, the first light beam having a wavelength λ_1 and the second light beam having a wavelength λ_2 where $\lambda_1 = M\lambda_2$. The first light beam includes two orthogonally polarized components differing in frequency by a first beat frequency, $F_{ref}(\lambda_1)$, and the second light beam includes two orthogonally polarized components differing in frequency by a

second beat frequency, $F_{ref}(\lambda_2)$, where $F_{ref}(\lambda_2) = M F_{ref}(\lambda_1)$, and M is an integer greater than 1. A polarization dependent beam splitter directs one of the orthogonally polarized components of each of the light beams to the reference mirror and the other of the orthogonally polarized components of each of the light beams to the stage mirror. The polarization dependent beam splitter also recombines the orthogonally polarized components after the orthogonally polarized components have been reflected by either the reference mirror or the stage mirror. A first detector measures the intensity of light in the first light beam after the orthogonally polarized components of the first light beam have been recombined by the polarization dependent beam splitter to generate a first detector signal having a magnitude equal to the light intensity at the first detector, the first detector signal oscillating at an instantaneous frequency of $F_1(t)$. A second measures the intensity of light in the second light beam after the orthogonally polarized components of the second light beam have been recombined by the polarization dependent beam splitter. The second detector generating a second detector signal having a magnitude equal to the light intensity at the second detector, the second detector signal oscillating at an instantaneous frequency of $F_2(t)$. A reference signal generator generates a reference signal that oscillates at $F_{ref}(\lambda_1)$. An optical path measurement circuit measures the difference in the number of oscillations of the second detector signal and the reference signal generator during the period in which the stage mirror moves from the first position to the second position. A correction term circuit measures the number of oscillations in a signal having an instantaneous frequency equal to $M F_1(t) - F_2(t)$ during the period in which the stage mirror moves from the first position to the second position. In the preferred embodiment of the present invention, $M=2$.

An embodiment of the present invention is described below, by way of example only, with reference to the accompanying drawing, in which:

Figure 1 is a block diagram of an embodiment of laser interferometer.

Referring now to Figure 1, there is shown a block diagram of an embodiment of laser interferometer 10 for measuring the difference in distance between a reference mirror 21 and a movable mirror 22. Light source 11 generates two orthogonally polarized split-frequency waves at 2 wavelengths, λ_1 and $\lambda_2 = \lambda_1/2$. The waves are shown as

two separate beams to simplify the drawing, however, it is to be understood that the two beams are coincident in space. The beam at λ_1 is shown at 12 and the beam at λ_2 is shown at 13. Each beam is composed of the two orthogonally polarized components that differ in frequency by 5-10 MHz. The optimal frequency difference is determined by the maximum speed at which the stage travels. A laser having the required properties is described in U.S. Patent 5,732,095, which is hereby incorporated by reference.

Each beam is split by polarization beam splitter 17 such that one component is directed to reference mirror 21 and the other component is directed to stage mirror 22. A quarter wave plate 14 provides a 90° rotation of the polarization of the components that are reflected from reference mirror. Hence, on returning to beam splitter 17, these components pass through the beam splitter and reach detectors 23 and 24 via polarization analyzer 25. Analyzer 25 generates a beat signal from the orthogonally polarized beams coming from the reference and measurement mirrors. It is oriented at 45° to the polarization directions of these beams. Similarly, a quarter wave plate 15 provides a 90° rotation of the polarization of the components that pass through beam splitter 17 and are reflected from stage mirror 22. Hence, on returning to beam splitter 17, these components are also reflected into detectors 23 and 24. Detector 23 has an appropriate filter to limit its detection to the light in the frequencies in beam 12, and detector 24 has a filter to limit its detection to the light of the frequencies in beam 13.

A third detector 27 and a second analyzer 28 generate a reference signal from the output of light source 11 at λ_2 . A non-polarizing beam splitter 16 is used to divert a portion of the laser output to detector 27 which has a filter that blocks light of wavelength λ_1 .

For the purposes of this discussion, it will be assumed that the two components of the beam having wavelength λ_1 differ by 10 MHz and that $M=2$, i.e., $\lambda_1 = 2\lambda_2$. Hence, the output of detector 27 will have a beat frequency of 10 MHz and is determined solely by the splitting in the laser line. The beat frequency generated by detector 24 will be Doppler shifted relative to this reference frequency by an amount that depends on the speed at which the stage is traveling.

The difference in frequency between the components of the beam at λ_2 is determined by the difference at λ_1 . Hence, in the present example, the output of detector 23 will have a beat frequency of 20 MHz Doppler shifted by an amount that depends on the speed at which the stage is traveling.

This embodiment is based on the observation that the optical path length, $P_{AB}(\lambda)$, corresponding to the mirror moving from position A to position B is related to distance L_{AB} moved by the mirror and the index of refraction of air at the measurement wavelength by the following formula:

$$P_{AB}(\lambda) = L_{AB} + \int_A^B [n(\lambda) - 1] dx \quad (1)$$

where $n(\lambda)$ is the index of refraction of air at λ . Applying Eq. (1) at the two frequencies and solving for L_{AB} ,

$$L_{AB} = P_{AB}(\lambda_2) - \frac{\alpha_2 [P_{AB}(\lambda_1) - P_{AB}(\lambda_2)]}{\alpha_1 - \alpha_2} \quad (2)$$

where

$$\alpha_i = \frac{n(\lambda_i) - 1}{\rho} \quad (3)$$

for $i=1, 2$. Here, ρ is the density of air. It should be noted that the Eq. (2) does not depend on ρ ; hence, the distance computed from Eq. (2) is corrected for any turbulence.

For AC interferometric measurements, the optical path length is related to the frequency difference of the two polarized states at the beam frequency Doppler shifted by the instantaneous stage speed at time. In particular,

$$P_{AB}(\lambda) = \frac{\lambda}{4\pi} \int_A^B [F_\lambda(t) - F_{ref}(\lambda)] dt \quad (4)$$

where, $F_{\lambda}(t)$ is the beat frequency measured at time, t , by the detector tuned to detect wavelength λ , and $F_{ref}(\lambda)$ is the reference beat frequency at wavelength λ , i.e., the beat frequency when the stage is not moving. As noted above, $\lambda_1 = 2\lambda_2$ and $F_{ref}(\lambda_2) = 2F_{ref}(\lambda_1)$. Hence,

$$P_{AB}(\lambda_1) - P_{AB}(\lambda_2) = \frac{\lambda_2}{4\pi} \int_A^B [2F_{\lambda_1}(t) - F_{\lambda_1}(t)] dt \quad (5)$$

It should be noted that the integral is merely the count accumulated by a counter whose input is the difference between twice the lower beat frequency and the higher beat frequency during the time the stage moves from position A to position B. In the preferred embodiment of the present invention, this difference is generated using a frequency doubling circuit 34 to double the beat frequency from detector 23 and a mixer 32 to form the difference of the doubled beat frequency and the beat frequency measured by detector 24. The resultant difference signal is integrated by correction generator 33, which also multiplies the correction by

$$\Gamma = \frac{\alpha_2}{\alpha_1 - \alpha_2} \quad (6)$$

The optical path at λ_2 is generated by circuit 31 which accumulates the difference between the beat frequency from detector 24 and the reference frequency from detector 27 during the period in which the stage moves from position A to position B. The accumulated difference is multiplied by $\lambda_2/4\pi$ to generate the optical path measurement, $P_{AB}(\lambda_2)$. Subtractor 34 provides the corrected distance measurement by computing the difference between the optical path measurement and the correction term.

The above-described embodiments utilize two beams that differ in frequency by a factor of two. However, it will be obvious to those skilled in the art from the preceding discussion that they may be practiced with two beams that differ in frequency by any integer factor.

The above-described embodiments also utilize specific circuitry for computing the difference of the beat frequencies. However, it will be obvious to

those skilled in the art from the preceding discussion that other circuits could be utilized. For example, the individual beat frequencies can be separately integrated over the movement of the stage and the correction term determined from the accumulated differences.

The disclosures in United States patent application number 09/227,998, from which this application claims priority, and in the abstract accompanying this application are incorporated herein by reference.

CLAIMS

1. Apparatus for measuring the change in position of a stage mirror with reference to a reference mirror when said stage mirror moves between first and second positions, said apparatus comprising: a light source for generating first and second coincident light beams, said first light beam having a wavelength λ_1 and said second light beam having a wavelength λ_2 where $\lambda_1 = M\lambda_2$, said first light beam comprising two orthogonally polarized components differing in frequency by a first beat frequency, $F_{ref}(\lambda_1)$ and said second light beam comprising two orthogonally polarized components differing in frequency by a second beat frequency, $F_{ref}(\lambda_2)$, where $F_{ref}(\lambda_2) = M F_{ref}(\lambda_1)$, M being an integer greater than 1; a polarization dependent beam splitter for directing one of said orthogonally polarized components of each of said light beams to said reference mirror and the other of said orthogonally polarized components of each of said light beams to said stage mirror and for recombining said orthogonally polarized components after said orthogonally polarized components have been reflected by either said reference mirror or said stage mirror; a first detector for detecting the intensity of light in said first light beam after said orthogonally polarized components of said first light beam have been recombined by said polarization dependent beam splitter, said first detector generating a first detector signal having a magnitude equal to the light intensity at said first detector, said first detector signal oscillating at an instantaneous frequency of $F_1(t)$; a second detector for detecting the intensity of light in said second light beam after said orthogonally polarized components of said second light beam have been recombined by said polarization dependent beam splitter, said second detector generating a second detector signal having a magnitude equal to the light intensity at said second detector, said second detector signal oscillating at an instantaneous frequency of $F_2(t)$; a reference signal generator for generating a reference signal that oscillates at said second beat frequency; an optical path measurement circuit for measuring the difference in the number of oscillations of said second detector signal and said reference signal generator during the period in which said stage mirror moves from said first position to said second position and for generating an optical path signal indicative of said difference; and a correction term circuit for measuring the number of oscillations in a signal comprising $MF_1(t) - F_2(t)$ during the period in which said stage mirror moves from

said first position to said second position and generating a correction signal indicative of said measured number of oscillations.

2. Apparatus as in claim 1, comprising a circuit for forming a linear weighted difference of said optical path signal and said correction signal.

3. Apparatus as in claim 1 or 2, wherein said correction term circuit comprises a frequency multiplying circuit for generating a signal having M times the frequency of said first detector signal and a mixer for subtracting said generated signal from said second detector signal.

4. Apparatus as in claim 1, 2 or 3, wherein $M=2$.

5. Apparatus as in any preceding claim, wherein said reference signal generator comprises a beam splitter for directing a portion of said second light beam onto a light detector operable to generate said reference signal.

6. A method of measuring the change in position of a stage mirror with reference to a reference mirror when said stage mirror moves between first and second positions, said method comprising: generating first and second coincident light beams, said first light beam having a wavelength λ_1 and said second light beam having a wavelength λ_2 where $\lambda_1 = M\lambda_2$, said first light beam comprising two orthogonally polarized components differing in frequency by a first beat frequency, $F_{ref}(\lambda_1)$ and said second light beam comprising two orthogonally polarized components differing in frequency by a second beat frequency, $F_{ref}(\lambda_2)$, where $F_{ref}(\lambda_2) = M F_{ref}(\lambda_1)$, M being an integer greater than 1; directing one of said orthogonally polarized components of each of said light beams to said reference mirror and the other of said orthogonally polarized components of each of said light beams to said stage mirror and for recombining said orthogonally polarized components after said orthogonally polarized components have been reflected by either said reference mirror or said stage mirror; detecting the intensity of light in said first light beam after said orthogonally polarized components of said first light beam have been recombined, generating a first

detector signal having a magnitude equal to the light intensity at said first detector, said first detector signal oscillating at an instantaneous frequency of $F_1(t)$; detecting the intensity of light in said second light beam after said orthogonally polarized components of said second light beam have been recombined, generating a second detector signal having a magnitude equal to light intensity, said second detector signal oscillating at an instantaneous frequency of $F_2(t)$; generating a reference signal that oscillates at said second beat frequency; measuring the difference in the number of oscillations of said second detector signal and said reference signal during the period in which said stage mirror moves from said first position to said second position and for generating an optical path signal indicative of said difference; and measuring the number of oscillations in a signal comprising $MF_1(t)-F_2(t)$ during the period in which said stage mirror moves from said first position to said second position and generating a correction signal indicative of said measured number of oscillations.

7. A method as in claim 6, comprising a linear weighted difference of said optical path signal and said correction signal.
8. A method as in claim 6 or 7, comprising generating a signal having M times the frequency of said first detector signal and subtracting said generated signal from said second detector signal.
9. A method as in claim 6, 7 or 8, wherein $M=2$.
10. A method as in any one of claims 6 to 9, comprising directing a portion of said second light beam onto a light detector operable to generate said reference signal.
11. Apparatus for measuring the change in position of a stage mirror substantially as hereinbefore described with reference to and as illustrated in the accompanying drawing.
12. A method of measuring the change in position of a stage mirror substantially as hereinbefore described with reference to and as illustrated in the accompanying drawing.



INVESTOR IN PEOPLE

Application No: GB 0000370.7
Claims searched: 1 - 12

14

Examiner: Guy Tucker
Date of search: 14 June 2000

Patents Act 1977 Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.R): G1A (ACEW)

Int Cl (Ed.7): G01B9/02; G01D5/26; G01N21/41, 21/45;

Other: Online: EPODOC, JAPIO, WPI

Documents considered to be relevant:

Category	Identity of document and relevant passage	Relevant to claims
X	WO 99/42787 A1 (ZYGO) see in particular the abstract, figure 1a, page 24 line 14 - page 26 line 8 & page 28 line 12 - page 38 line 18.	1 & 6 at least
X	WO 98/08214 A1 (ZYGO) see in particular the abstract, figure 1 and pages 12 - 18	1 & 6 at least
X	US 5838485 A (DE GROOT et al.) see in particular the abstract, figure 1, columns 7 - 10	1 & 6 at least
X	US 5404222 A (LIS) see in particular the abstract, column 2 line 36 - column 3 line 11, column 4 line 34 - column 5 line 31, column 6 line 67 - column 8 line 65,	1 & 6 at least

X Document indicating lack of novelty or inventive step
Y Document indicating lack of inventive step if combined with one or more other documents of same category.

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A Document indicating technological background and/or state of the art.
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E Patent document published on or after, but with priority date earlier than, the filing date of this application.